CONTINUOUSLY VARIABLE ANALOG MICRO-MIRROR DEVICE

TECHNICAL FIELD

This invention relates generally to micro-optical devices and optical beam steering and more particularly to a continuously variable analog micro-mirror device.

BACKGROUND

There are many applications for light-beam steering devices that have high spatial and time resolution and high brightness, including applications in display of information for education, business, science, technology, health, sports, and entertainment. Some light-beam steering devices, such as digital light-mirror arrays and deformographic displays, have been applied for large-screen projection. For white light, light modulators such as the reflective digital mirror arrays have been developed with high optical efficiency, high fill-factors with resultant low pixelation, convenient electronic driving requirements, and thermal robustness.

Macroscopic scanners have employed mirrors moved by electromagnetic actuators such as "voice-coils" and associated drivers. Micro-mirror devices have used micro-actuators based on micro-electro-mechanical-system (MEMS) techniques. MEMS actuators have also been employed in other applications

such as micro-motors, micro-switches, and valves for control of fluid flow. Micro-actuators have been formed on insulators or other substrates using micro-electronic techniques such as photolithography, vapor deposition, and etching.

A micro-mirror device can be operated as a light modulator for amplitude and/or phase modulation of incident light. One application of a micro-mirror device is in a display system. In such a system, multiple micro-mirror devices are arranged in an array such that each micro-mirror device provides one cell or pixel of the display. A conventional micro-mirror device includes an electrostatically actuated mirror supported for rotation about an axis of the mirror into either one of two stable positions. Thus, such a construction serves to provide both light and dark pixel elements corresponding to the two stable positions. For gray scale variation, binary pulse-width modulation has been applied to the tilt of each micro-mirror. Thus, conventional micro-mirror devices have frequently required a high frequency oscillation of the mirror and frequent switching of the mirror position and thus had need for high frequency circuits to drive the mirror. Binary pulse-width modulation has been accomplished by off-chip electronics, controlling on- or off-chip drivers.

Conventional micro-mirror devices must be sufficiently sized to permit rotation of the mirror relative to a supporting structure. Increasing the size of the micro-mirror device, however, reduces resolution of the display since fewer micro-mirror devices can occupy a given area. In addition, applied energies must be sufficient to generate a desired force needed to change the mirror position. Also, there are applications of micro-mirror devices that require positioning of the mirror in a continuous manner by application of an analog signal rather than requiring binary digital positioning controlled by a digital signal. Accordingly, it is desirable to minimize a size of a micro-mirror device so as to maximize the density of an array of such devices, and it is desirable as well to provide means for positioning the micro-mirror device in an analog fashion.

Some micro-mirrors have used a liquid-metal drop to support the mirror. Such a support allows the micro-mirror to adopt various positions in a continuous range, with tilting about axes with many different orientations.

While the various beam-steering devices have found widespread success in their applications, there are still unmet needs in the field of micro-optical beam steering, particularly for continuous-range analog beam steering.

BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the disclosure will readily be appreciated by persons skilled in the art from the following detailed description when read in conjunction with the drawings, wherein:

FIG. 1 is a schematic side elevation cross-sectional view of an embodiment of a micro-mirror device made in accordance with the invention.

FIG. 2 is a perspective view illustrating one embodiment of a portion of a micro-mirror device made in accordance with the invention.

FIG. 3 is an electrical schematic diagram of a first circuit embodiment made in accordance with the invention.

FIG. 4 is an electrical schematic diagram of a second circuit embodiment.

FIG. 5 an electrical schematic diagram of a third circuit embodiment.

FIG. 6 is an electrical schematic diagram of a fourth circuit embodiment.

DETAILED DESCRIPTION OF EMBODIMENTS

For clarity of the description, the drawings are not drawn to a uniform scale. In particular, vertical and horizontal scales may differ from each other and may vary from one drawing to another. In this regard, directional terminology, such as “top,” “bottom,” “front,” “back,” “leading,” “trailing,” etc., is used with reference to the orientation of the drawing figure(s) being described. Because components of the invention can be positioned in a number of different orientations, the directional terminology is used for purposes of illustration and is in no way limiting.

One aspect of the invention provides a micro-mirror device **10**. The micro-mirror device embodiment to be described first includes a substrate **20** having a surface **22** and a plate **30**. Plate **30** is spaced from the surface **22** of the substrate and oriented substantially parallel to the surface of the substrate such that plate **30** and the surface **22** of the substrate define a cavity **50** between them. A dielectric liquid **52** is disposed in the cavity and a reflective element **42** is interposed between the surface **22** of substrate **20** and plate **30**. Reflective element **42** is adapted to move to a selected position in a continuous range between a first position and at least one second position. Another aspect of the invention is a micro-mirror device **10** which relies on electrical to mechanical conversion to generate a force and cause movement or actuation of a body or element. Thus, micro-mirror device **10** is a MEMS device, a micro-electro-mechanical system.

In one embodiment, as described below, a plurality of micro-mirror devices **10** are arranged to form an array of micro-mirror devices. The array of micro-mirror devices may be used to form a display. Each micro-mirror device **10** constitutes a light modulator for modulation or steering of incident light. In an application to a display, each micro-mirror device may provide one cell or pixel of the display. Micro-mirror devices **10** may also be used in other imaging systems such as projectors and in optical addressing systems, as well as in instrumentation, such as spectrophotometers, plasmon resonance sensors, etc.

FIG. 1 illustrates one embodiment of a micro-mirror device **10**. In this embodiment, micro-mirror device **10** includes a substrate **20**, a plate **30**, and an actuating element **40**. Substrate **20** has a surface **22**. In one embodiment, surface **22** is formed by a trench or tub formed in and/or on substrate **20**. Plate **30** is oriented substantially parallel to surface **22** in this embodiment. Actuating element **40** is interposed between substrate **20** and plate **30** in cavity **50** and spaced from surface **22** of substrate **20** and from plate **30**.

In one embodiment, actuating element **40** is actuated so as to move between a first position **46** and a second position **48** relative to substrate **20** and plate **30**.

For example, actuating element **40** moves or tilts about an axis of rotation, tilting through a range of angles relative to substrate **20** and plate **30**. Thus, the instantaneous position of actuating element **40** may be characterized by an angle relative to substrate **20** or plate **30**. The axis of rotation of actuating element **40** may be parallel to substrate **20** or plate **30**. In FIG. 1, the axis of rotation of actuating element **40** is perpendicular to the page. In moving in the range between first position **46** and second position **48,** actuating element **40** may be in an intermediate position **47**. Intermediate position **47** of actuating element **40** is illustrated in FIG. 1 as being substantially horizontal and substantially parallel to substrate **20**. In some embodiments, intermediate position **47** may be a neutral or "rest" position occupied by actuating element **40** when no force is applied to cause movement or actuation of actuating element **40**. For other embodiments, a different neutral or "rest" position may be chosen. In FIG. 1, both first and second positions **46** and **48** of actuating element **40** are illustrated as being oriented at an angle relative to intermediate position **47**. Movement or actuation of actuating element **40** relative to substrate **20** and plate **30** is described in detail below.

In some embodiments, cavity **50** contains a dielectric liquid **52** such that actuating element **40** is in contact with dielectric liquid **52**. In one embodiment, cavity **50** is filled with dielectric liquid **52** such that actuating element **40** is submerged in dielectric liquid **52**. Thus, in such an embodiment, dielectric liquid **52** is disposed both between actuating element **40** and substrate **20** and between actuating element **40** and plate **30**. Thus, dielectric liquid **52** contacts or wets opposite surfaces of actuating element **40**. In another embodiment, cavity **50** is filled with dielectric liquid **52** such that actuating element **40** is positioned above dielectric liquid **52** and at least a surface of actuating element **40** facing substrate **20** is in contact with dielectric liquid **52**. Dielectric liquid **52** enhances actuation of actuating element **40**, increasing actuation force on actuating element **40** as generated by a given applied voltage as described below. For many applications, dielectric liquid **52** is substantially transparent and is clear or colorless in the visible spectrum. In addition, dielectric liquid **52** is chemically stable in electric fields, chemically stable with changes in

temperature, and chemically inert. In addition, dielectric liquid **52** has a low vapor pressure and is non-corrosive. Furthermore, dielectric liquid **52** has a high molecular orientation in electric fields and moves in an electric field. Dielectric liquid **52** has a relatively low dielectric constant and a relatively high dipole moment. In addition, dielectric liquid **52** is generally flexible and has pi electrons available. Dielectric liquid **52** can transfer heat within the micro-mirror device by conduction and convection. Examples of liquids suitable for use as dielectric liquid **52** include phenyl-ethers, either alone or in blends (e.g., 2-, 3-, and 5-ring), phenyl-sulphides, and/or phenyl-selenides. In one illustrative embodiment, examples of liquids suitable for use as dielectric liquid **52** include a polyphenyl ether (PPE) such as OS138 and olive oil.

For some applications, with a suitable dielectric liquid **52** and suitable orientation of substrate **20**, plate **30** may be omitted.

Plate **30**, if present, is a transparent plate **32.** In one embodiment, transparent plate **32** is a glass plate. Other suitable planar transparent or translucent materials, however, may be used. Examples of such materials include quartz and plastic.

Actuating element **40** includes a reflective element **42**. Reflective element **42** includes a reflective surface **144**. In one embodiment, reflective element **42** is formed of a uniform material having a suitable reflectivity to form reflective surface **144**. Examples of such a material include polysilicon or a metal such as aluminum. In another embodiment, reflective element **42** is formed of a base material such as polysilicon with a reflective material such as aluminum or titanium nitride disposed on the base material to form reflective surface **144**. In addition, reflective element **42** may be formed of a non-conductive material or may include or be formed of a conductive material.

As illustrated in the embodiment of FIG. 1, micro-mirror device **10** modulates light generated by a light source (not shown) located on a side of transparent plate **32** opposite of substrate **20**. The light source may include ambient and/or artificial light, for example. Input light **12**, incident on transparent plate **32**,

passes through transparent plate **32** into cavity **50** and is reflected by reflective surface **144** of reflective element **42** as output light **14**. Thus, output light **14** passes out of cavity **50** and back through transparent plate **32**. The direction of output light **14** is determined or controlled by the position of reflective element **42**. For example, with reflective element **42** in intermediate position **47**, output light **14** is directed in a first direction **141**. However, with reflective element **42** in second position **48**, output light **14** is directed in a second direction **142**. Thus, micro-mirror device **10** modulates or varies the direction of output light **14** generated by input light **12**. Thus, reflective element **42** can be used to steer light into, and/or away from, an optical system such as an optical imaging system.

In one embodiment, intermediate position **47** is a neutral position of reflective element **42** and represents a fully "ON" state of micro-mirror device **10** in that light is reflected, for example, to a viewer or onto a display screen, as described below. Thus, second position **48** is an actuated position of reflective element **42** and may represent a fully "OFF" state of micro-mirror device **10** in that light is not reflected, for example, to a viewer, though an aperture, or onto a display screen. Similarly, first position **46** is an actuated position of reflective element **42** and may represent a third state of micro-mirror device **10** in that light is reflected in a direction different than the directions for either intermediate position **47** or second position **48**. Furthermore, first position **46**, instead of intermediate position **47**, may represent a fully "ON" state of micro-mirror device **10**. At various positions between fully "ON" and fully "OFF" states of micro-mirror device **10**, output light **14** is directed into various intermediate directions, thus providing continuously variable steering of output light **14** to any direction between the two ends of the range.

FIG. 2 illustrates one embodiment of reflective element **42**, shown in a perspective view. Reflective element **42** has a reflective surface **144** and includes a substantially rectangular-shaped outer portion **180** and a substantially rectangular-shaped inner portion **184**. In one embodiment, reflective surface **144** is formed on both outer portion **180** and inner portion **184**.

Outer portion **180** has four contiguous side portions **181** arranged to form a substantially rectangular-shaped opening **182**. Thus, inner portion **184** is positioned within opening **182**. Inner portion **184** is positioned symmetrically within opening **182**. In FIG. 2, reflective element **42** is shown in intermediate position **47** (cf. FIG. 1).

In one embodiment, a pair of hinges **186** extends between inner portion **184** and outer portion **180**. Hinges **186** extend from opposite sides or edges of inner portion **184** to adjacent opposite sides or edges of outer portion **180**. Outer portion **180** is supported by hinges **186** along an axis of symmetry. More specifically, outer portion **180** is supported about an axis that extends through the middle of its opposed edges. Thus, hinges **186** facilitate movement of reflective element **42** between first position **46** and second position **48**, as described above (FIG. 1). More specifically, hinges **186** facilitate movement of outer portion **180** between first position **46** and second position **48** relative to inner portion **184**. In one embodiment, hinges **186** include torsional members **188** having longitudinal axes **189** oriented substantially parallel to reflective surface **144**. Longitudinal axes **189** are collinear and coincide with an axis of symmetry of reflective element **42**. Thus, torsional members **188** twist or turn about longitudinal axes **189** to accommodate movement of outer portion **180** between first position **46** and second position **48** relative to inner portion **184**. In other embodiments, hinges **186** include flexure members able to bend along longitudinal axes **189** oriented substantially parallel to reflective surface **144**.

In one embodiment, reflective element **42** is supported relative to substrate **20** by a support or post **24** extending from surface **22** of substrate **20**. More specifically, post **24** supports inner portion **184** of reflective element **42**. Post **24** is positioned within side portions **181** of outer portion **180**. Thus, outer portion **180** of reflective element **42** is supported from post **24** by hinges **186**. In this embodiment, it is outer portion **180** that tilts to various angular positions relative to surface **22** of substrate **20**.

Reflective element **42** is tilted to a desired position within its continuous range by differentially charging capacitor pads **60** and **62**. Separate voltages may be applied to capacitor pads **60** and **62** through conductive paths **61** and **63** respectively (FIG. 1). Capacitor pads **60** and **62** are not visible in FIG. 2.

Two variable capacitors **220** and **230** (illustrated schematically in FIGS. 3 – 6) are formed by the structure illustrated in the embodiment of FIGS. 1 and 2. Reflective element **42** serves as a movable plate for both variable capacitors **220** and **230**. Capacitor pads **60** and **62** serve as fixed plates. For simplicity and clarity, edge or fringe effects and stray capacitance are omitted from this description. Capacitor **220** consists generally of capacitor pad **60** and the nearest end of reflective element **42** (the left end as shown in FIG. 1), with dielectric liquid **52** as the capacitor's dielectric. Capacitor **230** consists generally of capacitor pad **62** and the nearest end of reflective element **42** (the right end as shown in FIG. 1), again with dielectric liquid **52** as the capacitor's dielectric. The capacitance values of capacitors **220** and **230** are coupled due to the fact that reflective element **42** is generally somewhat rigid. Thus, when reflective element **42** is in position **46**, the distance between capacitor pad **62** and the right end of reflective element **42** is relatively small (providing higher capacitance) while the distance between capacitor pad **60** and the left end of reflective element **42** is relatively large (providing lower capacitance). Thus, capacitor **230** has relatively larger capacitance than capacitor **220** when reflective element **42** is in position **46**. Conversely, when reflective element **42** is in position **48**, the distance between capacitor pad **62** and the right end of reflective element **42** is relatively large (providing lower capacitance) while the distance between capacitor pad **60** and the left end of reflective element **42** is relatively small (providing higher capacitance). Thus, capacitor **220** has relatively larger capacitance than capacitor **230** when reflective element **42** is in position **48**. When capacitor **220** increases in capacitance due to positioning of reflective element **42**, capacitor **230** decreases in capacitance, and *vice versa*. Thus, as reflective element **42** pivots, the two capacitance values vary inversely. Capacitance values of both variable capacitors **220** and **230** are enhanced by the dielectric constant of dielectric liquid **52**.

While the invention should not be construed as being limited to the consequences of any particular theory of operation, it is believed that micro-mirror device **10** performs its function by utilizing a linear relationship of position with differential capacitance. The differential capacitance of variable capacitors **220** and **230** (i.e., the difference between their instantaneous capacitance values) is linearly related to the position of reflective element **42**. Thus, the differential capacitance may be used to sense the position of reflective element **42**. The differential capacitance is linearly related to the position of reflective element **42** at every position within the full range of positions. If reflective element **42** is conductive along its entire length, capacitors **220** and **230** are effectively connected in series. An electrical coupling to the center pivoting axis of reflective element **42** provides a common connection to capacitors **220** and **230**. That electrical coupling may be made through post **24** (e.g., through a conductive via extending through post **24**) or may be made through either or both of hinges **186**.

In normal operation, reflective element **42** does not tilt far enough to touch capacitor pads **60** and **62**, which could short-circuit capacitors **220** and **230**. However, to ensure that the short-circuiting of capacitors **220** and **230** is prevented, conventional mechanical stops (not shown) may be provided, as known in the art of conventional binary micro-mirror structures.

FIGS. 3 – 6 are electrical schematic diagrams illustrating various embodiments of circuits accepting an analog electrical signal as their input and driving micro-mirror device **10**. Variable capacitors **220** and **230**, described above, form part of each circuit. As shown in FIG. 3, an operational amplifier **200** accepts as its non-inverting input **240** an analog signal for driving micro-mirror device **10**. The output of the differential capacitance sensing is coupled to the inverting input **250** of operational amplifier **200**. One of the capacitor pads **60** or **62** is connected to ground **260**. In the circuit configuration shown in FIG. 3, the operational amplifier **200** drives the capacitors **220** and **230** in order to equalize the voltages at its non-inverting and inverting inputs. Thus micro-mirror device **10** is actuated by the electrostatic forces between the capacitor plates of

variable capacitors **220** and **230**, moving reflective element **42** accordingly. The analog input signal moves reflective element **42** to any desired position within its range. Since both capacitors **220** and **230** exert forces on reflective element **42** to move it, micro-mirror device **10** is actuated with more force than a conventional device driven electrostatically on one side. Since both capacitors **220** and **230** include dielectric liquid **52**, the electrostatic force is enhanced by the dielectric constant of dielectric liquid **52**. FIGS. 4 and 5 show alternative circuit embodiments using one operational amplifier **200** or two operational amplifiers **200** and **210** respectively.

FIG. 6 shows an electrical schematic diagram illustrating a method for dithering (or "wobulating") the position of reflective element **42**. The normal analog signal is applied to input **255** to steer reflective element **42** to its desired position. The dithering signal is applied to input **245** and mixed with the normal analog signal by a resistor network formed by resistors **270, 275,** and **280.** The mixed signal with a dithering signal superimposed on the normal analog driving signal is applied to the non-inverting input **240** of operational amplifier **200.** Resistors **285** and **290** provide for the proper level of feedback signal level applied to inverting input **250**. The dither signal applied at input **255** may be a sine wave, triangle, or square wave, for example. It may be synchronized with another input source if desired, or it may be unsynchronized.

Operational amplifiers **200** and **210** and the associated components provide drive circuitry for micro-mirror device **10**. Such drive circuitry can be formed in substrate **20**, using known methods of semiconductor integrated circuit fabrication.

Thus an aspect of the invention is a micro-mirror device, including a substrate, a pair of electrodes disposed adjacent to the surface of the substrate and spaced apart from each other, a reflective element spaced from the surface of the substrate, and a dielectric liquid disposed at least between the reflective element and the pair of electrodes. The reflective element is adapted to be positioned at any position within a continuous range between a first position and

a second position in response to analog electrical signals applied to the pair of electrodes. In the embodiments illustrated, the first and second positions of the reflective element are oriented in directions on opposite sides of a neutral position of the micro-mirror device, but it is possible to make embodiments in which the first or second position of the reflective element is the neutral (unactuated) position of the micro-mirror device. Generally, the first position of the reflective element is oriented at an angle to the second position, and the first and second positions of the reflective element are both oriented at an angle to a neutral third position between the first and second positions.

Another aspect of the invention is a method of using such a micro-mirror device by electrically coupling to the pair of electrodes an operational amplifier operated by coupling the reflective element to the inverting input of the operational amplifier to provide position feedback. Applying an analog positioning signal to the non-inverting input of the operational amplifier actuates the micro-mirror device, whereby the reflective element is positioned at a selected position within a continuous range between a first position and a second position in response to the applied analog positioning signal. As described above, a dithering signal may also be mixed with the analog positioning signal.

Another aspect of the invention is a method of forming a micro-mirror device by providing a substrate, providing a plate spaced from the surface of the substrate and oriented substantially parallel to the surface of the substrate, thus defining a cavity between the plate and the substrate, disposing a dielectric liquid in the cavity, and interposing a reflective element between the surface of the substrate and the plate, the reflective element being adapted as described above to move to a selected position within a continuous range.

INDUSTRIAL APPLICABILITY

Devices made in accordance with the invention are useful in light-beam steering devices that have high spatial and time resolution, high brightness, and a continuous range of deflection angles, with low-frequency and low-power driving

requirements. They may also be used in imaging systems such as projectors, in optical addressing applications, and in instrumentation applications.

Although the foregoing has been a description and illustration of specific embodiments of the invention, various modifications and changes thereto can be made by persons skilled in the art without departing from the scope and spirit of the invention as defined by the following claims. For example, at least one additional pair of capacitor pads may be disposed and adapted for pivoting a reflective element of the micro-mirror device about a second, nonparallel axis.

What is claimed is: